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DEVELOPMENT OF THE FLOW-THROUGH UNIT IN AN ANNULAR CYCLONE CHAMBER FOR PRODUCING SILICATE MELTS

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The drawbacks of the production of sodium disilicate in glass-melting tank furnaces are described, and the expedience of melting soluble glass in an annular cyclone chamber using industrial sulfate waste is demonstrated. A method for the calculation of the flow-through part of the cyclone chamber for a preset output is proposed. The results of the calculations of a cyclone chamber and a whole aggregate with an output of 40 tons/day are provided, including the environmental, technical, and economical parameters of the production of sodium disilicate and liquid glass based it.

Glass melts and other silicate melts are usually produced in glass-melting tank furnaces that have a number of drawbacks: a short campaign, a substantial consumption of expensive refractories, significant capital investments and maintenance cost, and an inadmissible quantity of toxic emissions into the atmosphere.

Impure sodium disilicate and liquid glass produced from it are widely used in many sectors of industry and enjoy constant demand. Impure sodium disilicate is usually melted from a two-component soda batch. The cost of soda is 20 – 30 times higher than the cost of sand. An increased melting temperature accelerates the wear of the refractories, which restricts the possibility of producing a higher-melting high-modulus variety of sodium disilicate. At the same time, the production of high-modulus sodium disilicate decreases the consumption of material and ensures better consumer properties.

To eliminate the above drawbacks, one can upgrade the existing tank furnaces, but the effect is insignificant. The most promising line is the development of fundamentally new solutions. One of them is producing sodium disilicate in the cyclone chamber, which underwent prototype testing at the Borskii and the Salavatskii technical glass works [1 – 3]. A further upgrade of this design is a combination of a cyclone chamber and a refractory tank beneath it to form an annular cyclone chamber (ACC) with walls wholly made of lining slag with forced cooling (Fig. 1).

The ACC is heated by natural gas via burners located tangentially to the inner wall of the cyclone. The number of burners depends on the ACC efficiency. The batch is introduced by injectors via vertical lances, whose number is equal to the number of gas burners, into the annular volume, i.e., into a vortex of high-temperature fuel combustion products; it rapidly becomes heated in the gas suspension, and under the effect of the centrifugal force precipitates onto the walls of the cyclone chamber and, in the form of a melted film containing sand grains, trickles down the wall into the tank. The melting of the batch is completed in the tank intensely mixed by the vortex; the melt, via an opening in the side wall, arrives at the feeder, is discharged from that feeder, and becomes granulated in a water flow streaming along the chute. The waste gases are directed upward via the neck to the heat recovery system, undergo purification, and are released into the atmosphere. Sodium disilicate was successfully melted in the ACC on a laboratory stand at the Moscow Power Institute.

The use of an annular cyclone chamber with forced cooling of slag lining makes it possible to extend the campaign up to 7 – 10 years, to ensure the production of high-modulus sodium disilicate, to increase the specific output to 40 tons/day per 1 m^3 of the working chamber volume, or up to 20 tons/m^2 of the surface of the melt per day, to substantially (4 – 6 times) lower the consumption of expensive refractories, to decrease 6 – 8 times the capital investments, to reduce 3 – 6 times the production space required for the process, to save fuel and energy resources (by 30 – 40%), to decrease toxic emissions into the atmosphere (3.5 – 5 times for nitric oxide, and 1.5 times for dust), to accomplish the heating-up campaign of the furnace in several hours instead of 5 – 10 days, and to improve the labor conditions.

Replacing soda with the sulfate waste, which is normally sent to dumping grounds, may lower by an order of magnitude the cost of the batch and of the end product. The more complicated technology of sodium disilicate production is

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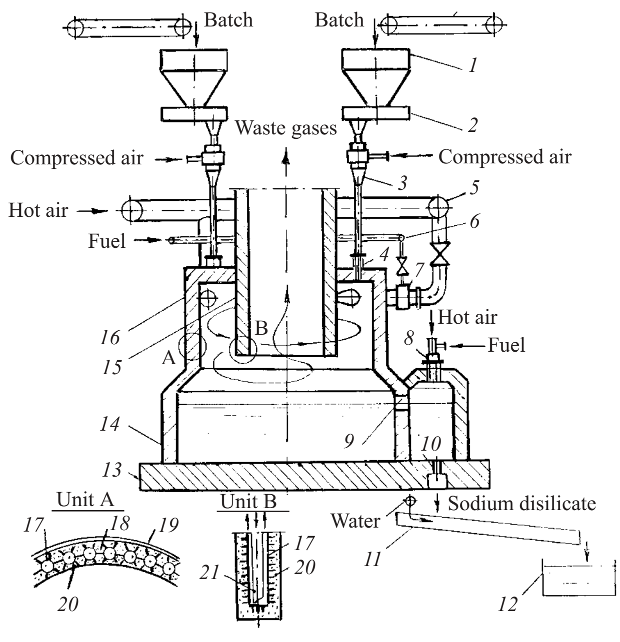

Fig. 1. Schematic design of the annular cyclone chamber with a tank for melting sodium disilicate: *1*) service bunker; *2*) batch feeder; *3*) injector for transporting the batch into the ACC; *4*) batch lance; *5*) hot air collector; *6*) natural gas collector; *7*) gas burner; *8*) feeder-heating burner; *9*) vent; *10*) feeder; *11*) granulation chute; *12*) granulation vessel; *13*) refractory floor, *14*) melting tank, *15*) neck; *16*) cyclone case; *17*) tenon pipes; *18*) heat insulation; *19*) steel casing; *20*) refractory tenon packing; *21*) pipes supplying water to the evaporative cooling system of the neck.

compensated by the economic and environmental advantages of using the sulfate batch. Indeed, to convert Na_2SO_4 into Na_2O, part of the sulfate has to be reduced to sulfide. The process can be carried out only with the gaseous reducing agent generated in incomplete combustion of natural gas, since any attempt to use coal for this purpose results in irreparable defects. The reduction reaction is complex and proceeds in several stages:

$$Na_2SO_4 + CO \text{ (or } H_2) \Leftrightarrow Na_2O + SO_2 + CO_2 \text{ (or } H_2O).$$

The reaction of sodium disilicate formation proceeds simultaneously, which shifts the equilibrium of the preceding reaction to the right:

$$Na_2O + nSiO_2 = Na_2O \cdot nSiO_2,$$

where $n = M_{sd}$ is the silicate modulus of the melt.

This process can be successfully implemented in the ACC.

Thus, the development of systems for producing silicate melts is topical.

Let us consider an example of producing silicate melt in an ACC with an efficiency of $G_m = 40$ tons/day of soluble glass with $M_{sd} = 3.0$ using sulfate waste from the Volgograd Aluminum Works (weight content, %): 92.40 Na_2SO_4, 5.90 Na_2CO_3, 1.20 NaCl, 0.28 SiO_2, 0.17 Al_2O_3, 0.02 FeO, and 0.03 MnO). The calculation of the material balance of the melting process using the Donskoi sand yielded the following results: specific consumption of sulfate waste $m_{sf} = 0.634$ kg/kg of glass granulate, consumption of sand $m_s = 0.762$ kg/kg of glass granulate, consumption of dry batch taking into account melting loss (5%) and entrainment (3%) — 1.451 kg/kg of glass granulate, moist batch (at $W_b = 10\%$) — 1.596 kg/kg of glass granulate, batch modulus $M_b = 3.158$, and yield of batch gasses $V_{bg} = 0.209$ m^3/sec.

The inner diameter of an ACC is determined using the dependence of the melt productivity on the process parameters obtained at the Moscow Power Institute as a consequence of a generalization of experimental research:

$$G_m = 1.07 \times 10^{-3}\,\bar{t}_g(10^{-3}\,\bar{t}_g - 1.1) \times (1 + 3.1\rho_b - 4.8 \times 10^{-9}\rho_b^2)(1 - 6.25 \times 10^{-4} d_b) \times (1 + 35.5 \times 10^{-3} D_c - 1.6 \times 10^{-3} D_c^2)\, D_c^{2.6},$$

where $\bar{t}_g = (T_{th}^2\, T_{wg}^2)^{0.25} - 273$ is the average gas temperature inside the ACC, °C (T_{th} and T_{wg} are the theoretical combustion temperature and the waste gas temperature at the entrance to the neck, K); ρ_b is the batch density, tons/m^3; d_b is the mean diameter of the batch particles, μm; and D_c is the inner diameter of the cyclone chamber, m.

The calculation indicates that under the preset productivity parameters ($G_m = 40$ tons/day), the inner diameter of the cyclone chamber should be equal to 1.9 m. The rest of the dimensions of the flow-through unit (in light) are taken as relative values: $\bar{x}_i = x_i/D_c$ (Fig. 2): $\bar{D}_{bun} = 1.0 - 1.2$, $\bar{h}_w = (0.8 - 1.0)\bar{H}_{bun}$, $\bar{H}_{bun} = 0.30 - 0.35$, $\bar{h}_{w\,neck} = 0.15 - 0.20$, $d'_{neck} = 0.58 - 0.63$, $d''_{neck} = d_{neck} + 2(100 - 120)$ mm, $\bar{H}_{neck} = 0.35 - 0.45$, $a = 0.5(D_{bun} - D_c)$, $b = 1.5d_n$, $D_{bl} = 0.5(D_c + d''_{neck})$.

In accordance with the recommendations the following parameters were obtained: $D_{bun} = 2280$ mm, $d'_{neck} = 1130$, $d''_{neck} = 1330$, $h_{w\,neck} = 335$, $h_m = h_{bun} = 600$, $a = 190$, $H_{neck} = 810$ mm.

To suppress the formation of nitric oxides, steam in the amount of 80 g per 1 m^3 of fuel is introduced into the natural gas collector in front of the burners [4]. The bottom 400 mm thick is made of Bacor bars.

After determining the cyclone chamber dimensions, the thermal balance of the chamber is calculated.

Heat Income Items, kW (%)

Fuel combustion	8168.7 (84.9)
Physical heat:	
fuel	7.6 (0.1)
air	1248.5 (13.0)
batch	138.9 (1.4)
Water steam	63.4 (0.6)
Total	9627.1 (100)

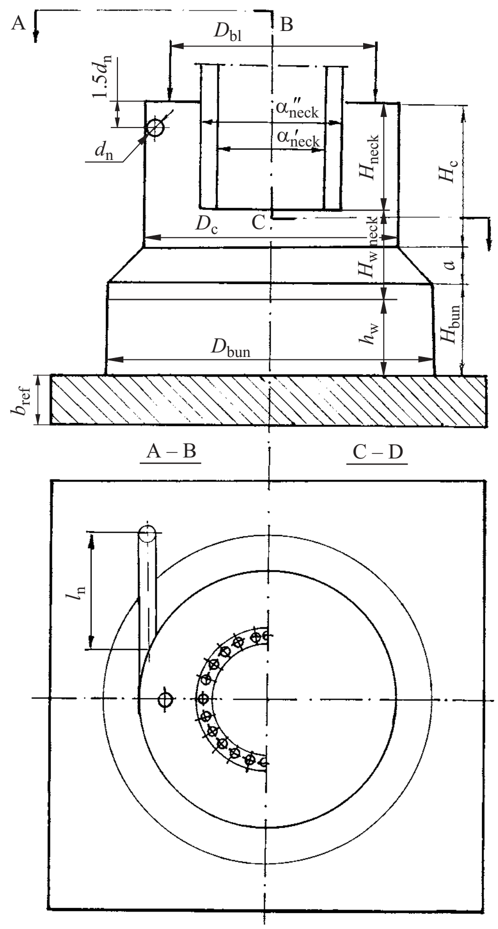

Fig. 2. Main geometrical parameters of the flow-through part of a circular cyclone chamber with a tank.

Heat Expenditure Items, kW

Melted glass	976.0 (10.1)
Batch melting	278.6 (2.9)
Spent in cooling of walls	1074.9 (11.2)
Waste gases	5077.9 (52.7)
Losses via the bottom	8.2 (0.1)
Radiation	150.2 (1.6)
Dust entrainment	31.6 (0.3)
Incomplete combustion	2029.5 (21.1)
Total	9627.1 (100)

The fuel flow rate amounted to $B = 1713$ m^3/h. Taking the entrance velocity of the gas-air mixture $w_{en} = 40 - 80$ m/sec, we set the burner nozzle diameter $d_n = (0.785B\,(1 + v_a^0)T_{en}/(3600n_n\,w_{en} \times 273))^{0.5}$.

The resulting configuration of the ACC needs to be checked for three critical modes and, when necessary, requires an adjustment of sizes. This recommendation is based on summarizing the experience of designing and starting-up laboratory and industrial silicate-melting ACC for a period of 30 – 40 years.

Verification of absence of acoustic resonance in fuel combustion in an ACC. The resonance phenomena do not arise if $|f_{fl} - f_{cc}| > 50$. The frequency of the natural oscillations of the flame $f_{fl} = w_{en}/(l_n - 0.5d_n)$. The natural frequency of the sound vibrations of the ACC is

$$f_{cc} = 0.31\sqrt{\frac{T_{neck}^{av} A}{V_{neck}^{cc}}},$$

where $A = \Sigma(S_i/l_i)$ is the acoustic conductivity of all openings (the burners, the neck, the batch lances, etc.), m; l_i is the distance, m, to a sound-reflecting obstacle from the ith opening with a cross-section S_i, m^2; V_{neck}^{cc} is the volume of the cyclone chamber filled with gases, m^3; $T_{neck}^{av} = (T_{wg}^{ch}\,T_{th})^{0.25}$ is the average temperature of the gases in the ACC volume, K (T_{wg} and T_{th} are the waste gas temperature and the theoretical temperature, K).

If $|f_{fl} - f_{cc}| \le 50$, it is necessary to modify the design of the ACC (the number of burners, their diameter, the chamber sizes, the distances between the openings in the ACC and the bends in connecting pipelines).

A calculation performed for the designed ACC with $d_n = 0.14$ m, $n_n = n_{fl} = 6$, $w_{en} = 60$ m/sec, and $T_{en} = 857$ K gives the values of $f_{fl} = 64.4$ and $f_{cc} = 4.6$ sec^{-1}. Thus, the designed chamber will operate in a resonance-free mode. A practical implementation of this method made it possible to eliminate noise and vibration in one of the furnaces at the Berezniki factory [5].

Such verification is needed for heavy-duty working chambers of any configuration.

Verification of choking of the neck. Such verification is needed since entrained melted particles from the gas vortex are deposited on the inner walls of the neck and trickle down in the form of a film, which is impeded by the friction of the gas counterflow. This may delay the flow of the viscous silicate melt and cause its accumulation on the walls (choking), which can lead to pressure pulsations inside the chamber, periodic drops in the weight of the material, etc.

Choking is absent when $w_g < w_g^{cr}$ [6].

The average gas velocity in the neck is

$$w_g = \frac{v_g T_g}{0.785 d_g'^2 \times 273},$$

where v_g is the gas flow rate in the neck, m^3/sec; T_g is the temperature of the gas flow in the neck, K; it can be taken equal to $(0.90 - 0.93)T_{wg}$.

The critical flow rate is

$$w_g^{cr} = \frac{2\rho_m\,g(2(\bar{\mu}_m - \ln\bar{\mu}_m - 1) - \ln^2\bar{\mu}_m)\delta_f}{\sqrt{C_z\rho_g(\bar{\mu}_m - \ln\bar{\mu}_m - 1)\ln\bar{\mu}_m}},$$

where g is the free fall acceleration, m/sec^2; $\bar{\mu}_m = \mu_0/\mu_m$ is the relative viscosity of the melt (μ_0 is the viscosity of the silicate melt at which its flow under the force of gravity stops, Pa · sec).

It is recommended for silicate melts to assume the flowing film thickness equal to $\delta_f = (3-10) \times 10^{-3}$ m and $\bar{\mu}_m = 5-20$. For low-viscosity melts (for instance, ore melts), $\delta_f = (1-4) \times 10^{-3}$ m and $\bar{\mu}_m = 40-100$.

A calculation of the operating conditions of the ACC indicated the absence of choking at the neck, since $w_g^{cr} = 255$ is significantly higher than $w_g = 13.7$ m/sec.

Verification of the hydrodynamic stability of the ACC tank. The high-temperature gas vortex in the ACC flows over the melt surface in the tank and transmits a part of its kinetic rotation energy, which leads to torsion of the melt. This accelerates by 2 – 3 orders of magnitude the dissolution of solid particles in the melt and ensures melt homogeneity, but it may lead to hydrodynamic instability of the tank, build-up of oscillations, and spraying of the melt.

The studies indicate that the melt in the tank is hydrodynamically stable if $\Phi_g < \Phi_g^{cr}$ [7, 8].

The actual criterion of the gas volume forcing is

$$\Phi_g = m_g \mu_g \rho_m (D_c \rho_g)^{-1} \mu_m^{-2},$$

where $m_g = v_g B \rho_g$ is the mass flow rate of the gases, kg/sec; μ_g and μ_m are the dynamic viscosities of the gases and the melt on the tank surface, Pa · sec; ρ_g and ρ_m are the densities of the gases and the melt at the temperatures and in the sites of their localization, kg/m^3.

The critical forcing criterion is

$$\Phi_g^{cr} = 1.02 \times 10^{-7} \mathrm{Ga}^{0.86} K_L,$$

where $\mathrm{Ga} = g(\rho_m/\mu_m)^2 D_c^3$ is the Galilee number; $K_L = K_1 K_2 K_3$ is coefficient accounting for the effect of the size and the shape of the ACC ($K_1 = 0.68 + 0.161\bar{H} + 0.13\bar{D}_{bun}$; $K_2 = 16.6\bar{h}_{wg}\bar{d}''_{neck}(1.12\bar{h}_{wg} + 1.2\bar{d}''_{neck} - \bar{h}_{wg}\bar{d}''_{neck}) + 22.3 \times (0.34\bar{h}_{wg} + 0.37\bar{d}''_{neck} - \bar{h}_{wg}\bar{d}''_{neck}) - (6.3\bar{h}_{wg}^2 + 7.46(\bar{d}'')_{neck}^2 + 1.74)$; K_3 depends on the number of the nozzles, $K_3 = 1.0$ at $n_n = 1$, $K_3 = 1.09$ at $n_n = 2$, and $K_3 = 1.12$ at $n_n \geq 3$).

For the considered tank configuration $\Phi_g^{cr} = 1.18 \times 10^{-3}$ and $\Phi_g = 0.145 \times 10^{-3}$, which indicates its hydrodynamic stability.

Below are listed the results of calculating a heat engineering system, which includes a recuperator, a recovery boiler operating together with the evaporative cooling of the ACC, as well as the ecological and engineering characteristics of the system.

The specific output of glass granulate from the bottom surface area is 9.8 tons/m^2 of the bottom surface area per day, the specific heat release generated in fuel combustion is 2.72 MW/m^3, the fuel utilization coefficient in the ACC is 19.8%, and in the whole system 59.5%. Damage to the ambient environment is estimated at 62 thousand rubles/year, which is 175 times lower than that of a glass-melting tank furnace with the same productivity (10.8 million rubles/year).

The number of working hours per year is 8496 h, the net discounted income is 27,455.56 thousand rubles/year, the net profit is 968.7 thousand rubles/year, the gross profitability on sales is 38.4%, and the net profitability 21.1%. The production cost of 1 ton of liquid glass is 986 rubles, including the energy component of 17% (the price of 1 ton of liquid glass is 1600 rubles).

The total gross profitability of this production is 52.3%, and the net profitability is 34.3%. The productivity is 3.33 tons/h of liquid glass, or 28,320 tons/year. The annual electricity consumption is 868 MW · h, the consumption of fuel is 7280 thousand m^3. The capital investment is 1.5 million rubles.

The above calculations and recommendations can serve as a basis for further upgrade of annular cyclone chambers intended for the production of silicate melts.

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